1 Defining and Assessing Soil Quality

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Recent interest in evaluating the quality of our soil resources has been stimulated by increasing awareness that *soil* is a critically important component of the earth's biosphere, functioning not only in the production of food and fiber but also in the maintenance of local, regional, and worldwide environmental quality. A recent call for development of a soil health index was stimulated by the perception that human health and welfare is associated with the quality and health of soils (Haberern, 1992). However, an international conference on assessment and monitoring of soil quality identified that defining and assessing soil quality and health is complicated by the need to consider the multiple functions of soil and to integrate the physical, chemical, and biological soil attributes that define soil function (Papendick & Parr, 1992; Rodale Inst., 1991). The alarming paucity of information on biological indicators of soil quality and methods for integrating physical, chemical, and biological soil properties with soil management practices to assess soil quality led to this special publication, *Defining Soil Quality for a Sustainable Environment*.

The purpose of this chapter is to discuss approaches to defining and assessing soil quality and to suggest one possible form for a soil quality index.

IMPORTANCE OF SOIL FUNCTION

We enter the 21st century with greater awareness of our technological capability to influence the global environment and of the impending crisis for sustaining life on earth (Sagan, 1992; Bhagat, 1990). Increasing concern

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for sustainable global development was reflected by the participation of heads of state and delegates from 178 countries at the United Nations Conference on Environment & Development, held in Rio de Janeiro in June 1992. Our past management of nature to meet the food and fiber needs of ever-increasing populations has taxed the resiliency of natural processes to maintain global balance and the cycling of energy and matter. Since the 1980s, severe degradation of the soil's productive capacity occurred on more than 10% of the earth's vegetated land as a result of soil erosion, atmospheric pollution, cultivation, over-grazing, land clearing, salinization, and desertification (World Resources Inst., 1992; Sanders, 1992). Drinking and surface and subsurface water quality has been jeopardized in many parts of the world by our choice of land management practices and the consequent imbalance of C and N cycling in soil. The present threat of global climate change and O_3 depletion, through elevated levels of atmospheric gases and altered hydrological cycles, mandates a better understanding of the effects of land management on soil processes. Soil management practices such as tillage, cropping patterns, and fertilization influence water quality, and it was recently shown that such management also influences atmospheric quality through changes in the soil's capacity to produce and/or consume important atmospheric gases such as CO_2, N_2O, and CH_4 (CAST, 1992; Mosier et al., 1991).

Soil is a dynamic, living, natural body that plays many key roles in terrestrial ecosystems. The components of soil include inorganic mineral matter (sand, silt, and clay particles), organic matter, water, gases, and living organisms such as earthworms, insects, bacteria, fungi, algae, and nematodes. There is continual interchange of molecules and ions between the solid, liquid, and gaseous phases that are mediated by physical, chemical, and biological processes. The importance of the microbial component of soil is often overlooked, because it is largely invisible to the naked eye. However, essential parts of the global C, N, P, and S, and water cycles are carried out in soil largely through microbial and faunal interactions with soil physical and chemical properties. Soil organic matter is a major terrestrial pool for C, N, P, and S, and the cycling and availability of these elements are constantly being altered by microbial mineralization and immobilization. Inorganic constituents of soil play a major role in retaining cations (through ion exchange) and nonpolar organic compounds and anions (through sorption reactions). Soil also serves as an essential reservoir of water for terrestrial plants and microorganisms and as a purifying medium through which water passes.

The thin layer of soil covering the earth's surface represents the difference between survival and extinction for most terrestrial life. Soil is a vital natural resource that is nonrenewable on a human time scale (Jenny, 1980). The quality of a soil is largely defined by soil function and represents a composite of its physical, chemical, and biological properties that (i) provide a medium for plant growth, (ii) regulate and partition water flow in the environment, and (iii) serves as an environmental buffer in the formation, attenuation, and degradation of environmentally hazardous compounds (Larson & Pierce, 1991). Soil serves as a medium for plant growth by providing physical support, water, essential nutrients, and oxygen for roots. The suitability of soil for sustaining plant growth and biological activity is a function of physical properties (porosity, water-holding capacity, structure, and tilth) and chemical properties (nutrient supplying ability, pH, salt content, etc.). Many of the soil's biological, physical, and chemical properties are a function of soil organic matter content. Soils play a key role in completing the cycling of major elements required by biological systems, decomposing of organic wastes, and detoxifying certain hazardous compounds. The key role played by soils in recycling organic materials into CO_2 and water and the degrading of chemical pollutants is manifest through microbial decomposition, chemical hydrolysis, complexation, and sorption reactions. The ability of a soil to store and transmit water is a major factor regulating water availability to plants and transport of environmental pollutants to surface and groundwater.

Mechanical cultivation and the continuous growing of row crops resulted in soil loss through erosion, decreases in soil organic matter content, and the concomitant release of CO_2 to the atmosphere (Houghton et al., 1983). Intensive crop production also resulted in excessive loss of topsoil through wind and water erosion. Decreased organic matter content and the use of large tillage and harvesting equipment has decreased structure, tilth, water holding capacity, water infiltration, and increased compaction. Development of saline and sodic soils after initiation of cultivation resulted from both inefficient irrigation techniques and natural processes. In certain areas, improper disposal of hazardous, recalcitrant chemical pollutants contaminated soils, so they are unsuitable for crop production or development and pose a threat to environmental quality and animal health. As a result of the above, we conclude that the quality of many soils in the USA has declined significantly since cultivation was initiated.

The Chinese saying, "The soil is the mother of all things," is a simple statement of the importance of soil to life of all living creatures. Soil function is essential to the sustainability of soil to life of all living creatures. As such, the ability to define and assess soil quality is essential to development, performance, and evaluation of sustainable land and soil management systems. Two important uses for soil quality assessment are (i) as a management tool or aid for farmers and (ii) as a measure of sustainability, of what is happening to our soils, and what we have to leave our grandchildren. We have a responsibility of returning to the soil the vitality it shares with us and to ensure that vitality for generations to come; "As we work our land to produce food, will we leave a legacy of gardens or deserts?" (Haberern, 1992). Our approaches to defining and assessing soil quality should be shaped by these end uses.

DEFINING SOIL QUALITY

Much like air or water, the *quality* of soil has a profound effect on the health and productivity of a given ecosystem and the environments related to it. However, unlike air or water for which we have quality standards, soil quality has been difficult to define and quantify. Many people, including the senior author of this chapter only a short time ago, believe that soil quality is an abstract characteristic of soils that can't be defined, because it depends on external factors such as land use and soil management practices, ecosystem and environmental interactions, socioeconomic and political priorities, and so on. Perceptions of what constitutes a *good* soil vary depending on individual priorities with respect to soil function. However, to manage and maintain our soils in an acceptable state for future generations, *soil quality* must be defined, and the definition must be broad enough to encompass the many facets of soil function.

Attempts to define soil quality should begin with a definition of the word *quality*. According to *Webster's Third New International Dictionary* (Grove, 1986), the word *quality* is a noun derived from the Latin word *qualitas* meaning *of what kind*. Usages and definitions in English include: (i) essential character: NATURE or KIND; (ii) a distinctive inherent feature or attribute: PROPERTY or VIRTUE; (iii) a character position or role: CAPACITY; (iv) degree of excellence: GRADE or CALIBER. *Soil quality* encompasses all these usages of the word *quality* in that it includes the nature and properties or attributes of soil as they relate to the capacity of soil to function effectively. Several definitions of soil quality that have recently been proposed are as follows:

> Soil qualities—Inherent attributes of soils that are inferred from soil characteristics or indirect observations (e.g., compactibility, erodibility, and fertility).
> (SSSA, 1987)
>
> The ability of soil to support crop growth which includes factors such as degree of tilth, aggregation, organic matter content, soil depth, water holding capacity, infiltration rate, pH changes, nutrient capacity, and so forth.
> (Power & Myers, 1989)
>
> The capacity of a soil to function in a productive and sustained manner while maintaining or improving the resource base, environment, and plant, animal, and human health.
> (NCR-59 meeting minutes, Madison, WI, September, 1991)
>
> The capacity of a soil to function within the ecosystem boundaries and interact positively with the environment external to that ecosystem.
> (Larson & Pierce, 1991)
>
> The capability of soil to produce safe and nutritious crops in a sustained manner over the long-term, and to enhance human and animal health, without impairing the natural resource base or harming the environment.
> (Parr et al., 1992)
>
> Simply put: "Fitness for use." (Pierce & Larson, 1993)

Common to all these definitions of soil quality is the capacity of soil to function effectively at present and in the future. Confusion as to what *soil quality* means often results from failure to identify the major issues of concern with respect to soil function. These issues were identified at a recent conference on assessment and monitoring of soil quality (Rodale Inst., 1991) as:

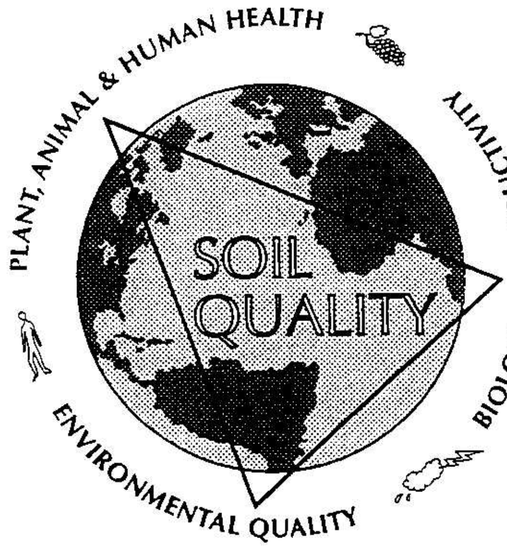

Fig. 1-1. Major issues or components that define soil quality.

1. Productivity—the ability of soil to enhance plant and biological productivity.
2. Environmental quality—the ability of soil to attenuate environmental contaminants, pathogens, and offsite damage.
3. Animal health—the interrelationship between soil quality and plant, animal, and human health (see Fig. 1-1).

We propose in this chapter to define soil quality as follows:

The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health.

ASSESSMENT OF SOIL QUALITY

Our ability to assess soil quality and identify key soil properties that serve as indicators of soil function is complicated by the many issues defining quality and the multiplicity of physical, chemical, and biological factors that control biogeochemical processes and their variation in time, space, and intensity. Practical assessment of soil quality requires consideration of these functions and their variations in time and space (Larson & Pierce, 1991). Soil quality assessment, however, is invaluable to determining the sustainability of land management systems in the near and distant future. A soil quality index is needed to identify problem production areas, make realistic estimates of food production, monitor changes in sustainability and environmental quality as related to agricultural management, and assist federal and state agencies in formulating and evaluating sustainable agricultural and land-use policies (Granatstein & Bezdicek, 1992). Of particular note is *how soil quality assessment can be used to evaluate the benefits from public investment in farm policy programs.*

Land management is sustainable only when it maintains or improves resource quality, specifically the quality of air, soil, water, and food resources. Soil quality assessment provides a basic means to evaluate the sustainability of agricultural and land management systems. Soils have various levels of quality that are basically defined by stable natural or inherent features related to soil-forming factors and dynamic changes induced by soil management (Pierce & Larson, 1993). Detecting changes in the dynamic component of soil quality is essential to evaluating the performance and sustainability of soil management systems. Pierce and Larson (1993) recently proposed an approach based on establishing a minimum data set of temporarily variable soil properties and pedotransfer functions. Pedotransfer functions serve to relate soil characteristics and properties with each other in evaluating soil quality and also in estimating soil attributes that are difficult to measure. This approach relies on available soil surveys for input data and simulation models to design sustainable management systems and establish soil standards for managing soil quality.

Basic Soil Quality Indicators

A system to assess the health or quality of soil can be likened to a medical examination for humans (Larson & Pierce, 1991). In a medical exam, the physician takes certain key measurements such as temperature, blood pressure, pulse rate, and perhaps certain blood chemistries as basic indicators of body system function. If these basic health indicators are outside the commonly accepted ranges, more specific tests may be conducted to help identify the cause of the problem and find a solution. For example, excessively high blood pressure may indicate a potential for system failure (death) through stroke or cardiac arrest. The problem of high blood pressure may result from the lifestyle of the individual due to improper diet or high stress level. To assess a dietary cause for high blood pressure, the physician may request a secondary blood chemistry test for cholesterol, electrolytes, etc. Assessment of stress level as a causative factor for high blood pressure is less straightforward and generally involves implementing some change in lifestyle followed by periodic monitoring of blood pressure to assess the effect of change. This is a good example of using a basic indicator both to identify a problem and to monitor the effects of management on the health of a system.

A set of basic indicators of soil health or quality have not been previously defined, largely due to the difficulty in defining and identifying what soil quality represents and how it can be measured. The need for basic indicators of soil quality is indicated by the question commonly posed by farmers, reserachers, and conservationists: "What measurements should I make to evaluate the effects of management on soil function now and in the future?" Our ability to identify basic soil properties that serve as indicators of soil quality is complicated by the many physical, chemical, and biological factors involved and their varying interactions in time, space, and intensity. However, one place to start is by identifying a basic list of measurable soil properties that define the major processes functioning in soil and ensure that the measurements we are making reflect conditions as they exist in the field. To be practical for use by scientists, farmers, extension workers, conservationists, ecologists, and policymakers over a range of ecological and socioeconomic situations, the set of basic soil quality indicators should meet the following suitability criteria:

1. Encompass ecosystem processes and relate to process oriented modeling.
2. Integrate soil physical, chemical, and biological properties and processes.
3. Be accessible to many users and applicable to field conditions
4. Be sensitive to variations in management and climate
5. Where possible, be components of existing soil data bases.

It is essential that basic soil quality indicators relate to ecosystem functions such as C and N cycling (Visser & Parkinson, 1992) and are components of driving variables for process-oriented models that emulate the ways ecosystems function. Evaluating the diverse effects of climate and management on soil function requires integration of basic physical, chemical, and biological indicators. *Too often scientists confine their interests and efforts to the discipline with which they are most familiar.* Microbiologists may confine their studies to microbial populations in the soil with little or no regard for soil physical or chemical characteristics that define the limits of microbial activity or that of other life forms. The approach to defining soil quality indicators must be holistic and not reductionistic. The indicators chosen must be accessible, or measurable, by as many people as possible and not limited to a select cadre of research scientists. Some indicators must be measured in the field to relate laboratory measurements to field conditions. One example is soil bulk density. Laboratory analyses for soil organic matter, N contents, etc. are commonly expressed on a gravimetric, or weight basis. These results are used to evaluate the effects of field management on soil quality as related to changes in organic matter or N content in the field. However, comparisons should not be made using gravimetric data, because soils are commonly sampled as a volume of soil to a specific depth. The specific concentration of a component in that volume of soil can change as the soil sample is prepared for analysis in the lab due to sieving, mixing, and drying. Thus expression of analytical results as concentration on a weight (gravimetric) basis does not accurately reflect the actual content or concentration for the soil depth sampled in the field. Also, soil bulk density frequently varies with management, depth of sampling, and time of year; valid comparison of management systems at a point in time or the same management system across time cannot be made without first adjusting results to a volumetric basis. Consequently, the inclusion of bulk density in a set of basic soil indicators is critical to proper interpretation of the importance of change in magnitude in other chemical and biochemical soil components.

Basic soil quality indicators should also be sensitive to variations in management or climate. If indicators of soil quality are insensitive to changes in management and climate, they will be of little use in monitoring changes in soil quality and proposing management changes to enhance soil quality. On the other hand, indicators of long-term changes in soil quality should not be confounded by short-term changes caused by seasonal weather patterns.

Wherever possible, basic indicators of soil quality should be properties or attributes that already exist in soil data banks. But we are faced with a formidable task in defining soil quality and the effects of management on sustainability. Basic indicators of soil quality will need to be compared with standards for a range of soils, climates, and management situations. Available data bases will be invaluable to formulation of standards, critical values, and thresholds for soil quality indicators.

A proposed set of basic soil quality indicators that meet many of the above-mentioned suitability criteria are given in Table 1-1. It should be emphasized that this is a set of *basic* indicators for initial characterization of soil quality. Other secondary measurements will likely be needed as dictated by existing data banks and specific climatic, geographic, and socioeconomic conditions or as indicated by assessment of basic indicators. Important soil quality indicators, not included in Table 1-1, are soil cation exchange capacity (CEC) and aggregate stability. However, CEC can be estimated from soil organic matter level, pH, and clay content. Inferences about soil aggregation can be made from organic matter content, soil infiltration rate after wetting, and soil bulk density (after wetting), which are included as basic indicators. However, a systematic cataloging of ranges and threshold values for these indicators will be needed to interpret the significance of changes in soil function and biological activity.

Larson and Pierce (1991) proposed that a minimum data set (MDS) be adopted for assessing the health of world soils and that standardized methodologies and procedures be established to assess changes in soil quality. They gave an example of a MDS of selected soil attributes for use in monitoring soil quality and changes with time (Table 1-2). Their choice of soil attributes for inclusion in the MDS was dictated by: (i) the need for selecting attributes sensitive to management and for which changes could be detected in a relatively short time, (ii) attributes for which measurement methodologies or data sets are accessible to most people, and (iii) attributes for which pedotransfer functions (Bouma, 1989) can be defined to interrelate soil properties and detect levels of soil quality. Many of the basic soil quality indicators given in Table 1-1 were taken from the MSD (Table 1-2) proposed by Larson and Pierce (1991).

The importance of standardized sampling methodologies and threshold values for interpretation of soil quality indicators cannot be over emphasized. The data presented in Table 1-3 represent measurements of soil quality indicators on soil samples from three farms in western Nebraska. The

Table 1-1. Proposed soil physical, chemical, and biological characteristics to be included as basic indicators of soil quality.

Soil characteristic	Methodology	Reference for methodology or interpretation, comments
	Physical	
Soil texture	Hydrometer method	Gee & Bauder, 1986
Depth of soil and rooting	Soil coring or excavation	Taylor & Terrell, 1982
Soil bulk density and infiltration†	Field determined using infiltration rings	Blake & Hartge, 1986
Water holding capacity†	Field determined after irrigation of rings	Cassel & Nielsen, 1986
Water retention characteristics	Water content at 33 and 1500 kPa tension	Klute, 1986
Water content†	Gravimetric analysis; wt. loss, 24 h at 105 °C	Sampled in field before and after irrigation
Soil temperature†	Dial thermometer or hand temperature probe	Measured at 4-cm soil depth
	Chemical	
Total organic C and N	Wet or dry combustion, *volumetric basis*‡	Nelson & Sommers, 1982; Schulte, 1988
pH	Field or lab determined, pocket pH meter	Eckert, 1988; 1:1 soil/water mixture
Electrical conductivity	Field or lab, pocket conductivity meter	Dahnke & Whitney, 1988; 1:1 soil/water
Mineral N (NH_4 and NO_3), P, and K	Field or lab analysis, *volumetric basis*	Gelderman & Fixen, 1988; Knudsen & Beegle, 1988; 2 *M* KCl extract for NH_4 and NO_3
	Biological	
Microbial biomass C and N	Chloroform fumigation/incubation, *volumetric basis*	Parkinson & Paul, 1982
Potentially mineralizable N	Anaerobic incubation, *volumetric basis*	Keeney, 1982
Soil respiration†	Field measured using covered infiltration rings, lab measured in biomass assay	Anderson, 1982; CO_2-specific gas analysis tubes (Draeger)
Biomass C/Total org. C ratio	Calculated from other measures	Estimate of ecosystem stability; Visser & Parkinson, 1992; Chapt. 5, this book
Respiration/biomass ratio	Calculated from other measures	Visser & Parkinson, 1992; Chapt. 5, this book

† Measurements taken simultaneously in field for varying management conditions, landscape locations, and time of year.
‡ Gravimetric results must be adjusted to volumetric basis using field measured soil bulk density for meaningful interpretations.

Table 1-2. Soil attributes and methodologies for measurement to be included in a minimum data set (MDS) for monitoring soil quality (after Larson & Pierce, 1991).

Soil attribute	Methodology
Nutrient availability	Analytical soil test
Total organic C	Dry or wet combustion
Labile organic C	NH_4-N release from hot KCl digest
Particle size	Pipette or hydrometer methods
Plant-available water capacity	Best determined in the field or from water desorption curve
Soil structure, form	Bulk density from intact soil cores and field measured permeability or K_{sat}
Soil strength	Bulk density or penetration resistance
Maximum rooting depth	Crop specific, depth of roots or standard
pH	Glass/calomel electrode, pH meter
Electrical conductivity	Conductivity meter

producer on one of these farms used an innovative tillage management system that provided raised beds allowing the soil to warm faster in the spring, drain better, and form large aggregates (clods) to protect the soil from wind and water erosion. The farmer interpreted the 1.4-fold higher respiration, 5- to 15-fold greater total microbial biomass, and increased fungal biomass of his soil as compared with his neighbors soils as indicative of better *quality*. However, two issues related to interpretation of these measurements need further discussion. The first issue involves interpretation of laboratory results in relation to actual microbial processes in the field. The laboratory findings represent only potential differences, since the respiration measurements were conducted under conditions of optimal temperature and moisture, and results were not adjusted for soil bulk densities in the field at time of sampling. Actual differences could be 20 to 30% lower after adjusting for soil bulk density, since tilled areas would have bulk densities as low as 1.0 g cm^{-3} and nontilled areas as high as 1.2 to 1.3 g cm^{-3}. Secondly, without reference guidelines it is difficult to interpret the relevance of these measurements to soil quality. For example, the higher respiration and biomass of bedded ridges could reflect enhanced nutrient cycling and soil aggregation, both of which are considered positive soil quality attributes. However, a respiration rate of 84 mg C kg $soil^{-1}$ d^{-1} might also represent depletion of soil C pools and soil organic matter. Assuming optimal conditions for soil respiration might

Table 1-3. Respiration and microbial biomass of 0- to 15-cm surface soils sampled from western Nebraska wheat fields in February 1991 (Parkin, 1991, unpublished data).

Area sampled	Soil respiration	Total microbial biomass	Fungal biomass†
	mg C kg^{-1} d^{-1}	mg C kg^{-1}	mg ergosterol kg^{-1}
Chemical-fallow farm	59	48	1.4
Conventional farm	54	18	0.9
Raised bed farm			
Ridge	84	262	2.4
Furrow	64	95	1.0

† Ergosterol as an estimate of fungal biomass (see Chapt. 16, this book).

occur for a 30-d period each year, the C loss for a 15-cm depth of soil in the bedded ridge would equal 3000 kg C yr^{-1}. This is three times the wheat (*Triticum aestivum* L.) residue C returned to this area (1000 kg C ha^{-1} yr^{-1}) and suggests a depletion of soil C reserves and long-term soil stability. From this standpoint, the high respiration rate observed would be undesirable and could detract from future soil quality. Clearly, additional guidelines for interpretation of soil quality indicators are badly needed.

Dynamic changes in soil quality indices and the many components of quality mandate temporal measurements and an evaluation approach that weighs the importance of various issues. As illustrated by the data presented in Table 1-4, evaluation of soil quality indicators varies during the growing season. The overall significance of soil quality indices such as microbial biomass N, potentially mineralizable N, and soil NO_3 levels with respect to crop productivity and environmental quality varies with time of year and agricultural management practice. For example, higher levels of microbial biomass and potentially mineralizable N, and lower levels of NO_3-N, in early spring (10 April) for alternative as compared with conventional management represent enhanced environmental quality due to lower potential N leaching losses during the nongrowing season but a potential limitation to corn (*Zea mays* L.) productivity. Decreases in biological N pools and corresponding increases in soil NO_3-N with alternative management during the growing season resulted in optimal final corn yield. These data illustrate the need to balance considerations for environmental quality with those for sustainable crop production. The alternative management system successfully reduced the inputs of synthetic chemicals, reduced the potential off-season losses of N, and maintained corn productivity by synchronizing the release of plant-available NO_3 from soil organic N sources with maximum plant need during the growing season. It is important to note, however, that the relative

Table 1-4. Management and cover crop effects on N pools in surface soil (0-30 cm) and related changes during the corn growing season in Pennsylvania (after Doran & Smith, 1991).

Management date	Microbial biomass N	Potentially mineralizable N	Nitrate N
	kg N ha^{-1}		
Alternative (corn-clover-winter wheat-soybean rotation + vetch cover crop)†			
10 April	121	1260	9
15 May‡	113	1260	39
12 June	75	1180	142
14 July	122	1220	99
Conventional (corn-soybean rotation with herbicides and fertilizer)			
10 April	92	990	42
15 May	56	950	56
12 June§	64	990	83
14 July	103	1020	106

† Corn, *Zea mays* L.; clover, *Trifolium* sp.; winter wheat, *Triticum aestivum* L.; soybean, *Glycine max* (L.) Merr.; vetch, *Vicia villosa* sp.

‡ Hairy vetch cover crop (182 kg N ha^{-1}) plowed into soil on 8 May.

§ 112 kg N ha^{-1} of ammonium nitrate fertilizer sidedressed on 17 June.

importance of soil quality issues and interpretation of soil quality issues varied with time of year.

Soil Quality Index—One Approach

There is general consensus that soil quality encompasses three broad issues; (i) plant and biological productivity, (ii) environmental quality, and (iii) human and animal health (Parr et al., 1992; Granatstein & Bezdicek, 1992; Arshad & Coen, 1992; Hornick, 1992). Therefore, any protocol designed to determine soil quality must provide an assessment of the function of soil with regard to these three issues. To effectively do this, the soil quality assessment must incorporate specific performance criteria for each of the three elements listed above, and it must be structured in such a way as to allow for quantitative evaluation and unambiguous interpretation.

Soil quality has been described as an inherent attribute of soil that may be inferred from its specific characteristics such as those presented in Table 1-2. However, measurement of the suite of properties listed in Table 1-2 will yield little insight into soil quality without specific criteria or guidelines for interpretation.

Two different approaches have been proposed for establishing reference criteria for assessing the quality of soil: (i) conditions of the native soil or (ii) conditions that maximize production and environmental performance (Granatstein & Bezdicek, 1992). For agricultural systems that are intensively managed we have adopted the latter approach and present below a framework for the evaluation of soil quality based on the function of soil.

A performance-based index of soil quality must provide an evaluation of soil function with regard to the major issues of (i) sustainable production, (ii) environmental quality, and (iii) human and animal health. To facilitate the development of specific performance criteria, we recommend that these three issues be further defined. *Sustainable production* can be defined in terms of plant production and resistance to erosion. *Environmental quality* can be defined in terms of groundwater quality, surface water quality, and air quality. *Human and animal health* can be defined in terms of food quality, which encompasses safety, and nutritional composition. Thus, we propose the following index of soil quality as a function of six specific soil quality elements (Eq. [1]):

$$SQ = f(SQ_{E1}, SQ_{E2}, SQ_{E3}, SQ_{E4}, SQ_{E5}, SQ_{E6}) \quad [1]$$

where the specific soil quality elements (SQ_{Ei}) are defined as follows:

SQ_{E1} = food and fiber production
SQ_{E2} = erosivity
SQ_{E3} = groundwater quality
SQ_{E4} = surface water quality
SQ_{E5} = air quality
SQ_{E6} = food quality

The advantage of this approach is that the functions of soil can be assessed based on specific performance criteria established for each element, for a given ecosystem. For example, yield goals for crop production (SQ_{E1}); limits for erosion losses (SQ_{E2}); concentration limits for chemical leaching from the rooting zone (SQ_{E3}); nutrient, chemical, and sediment loading limits to adjacent surface water systems (SQ_{E4}); production and uptake rates for trace gases that contribute to O_3 destruction or the greenhouse effect (SQ_{E5}); and nutritional composition and chemical residue of food (SQ_{E6}).

At this time there is not sufficient information to identify, with certainty, the optimum functional relationship used to combine the different soil quality elements shown in Eq. [1]; however, one possibility is a simple multiplicative function (Eq. [2]).

$$SQ = (K_1SQ_{E1})(K_2SQ_{E2})(K_3SQ_{E3})(K_4SQ_{E4})(K_5SQ_{E5})(K_6SQ_{E6}) \quad [2]$$

where K = weighting coefficients.

In a manner analogous to the soil tilth index of Singh et al. (1990), weighting factors are assigned to each soil quality element, with the relative weights of these coefficients being determined by geographical considerations, societal concerns, and economic constraints. For example, in a given region, food production may be the primary concern, and elements such as air quality may be of secondary importance. If such were the case, SQ_{E1} would be weighted more heavily than SQ_{E5}. Thus, this framework has an inherent flexibility in that the precise functional relationship for a given region, or a given field, is determined by the intended use of that area or site, as dictated by geographical and climatic constraints as well as socioeconomic concerns.

Implementation of the Index

It is proposed that each soil quality element in this index be evaluated with regard to five specific soil functions, which define the capacity of soil to (i) provide a medium for plant growth and biological activity, (ii) regulate and partition water flow through the environment, and (iii) serve as an effective environmental filter (Larson & Pierce, 1991). These specific soil function factors are:

SF_1 = ability to hold, accept, and release water to plants, streams, and subsoil (water flux)
SF_2 = ability to hold, accept, and release nutrients and other chemicals (nutrient and chemical fluxes)
SF_3 = promote and sustain root growth
SF_4 = maintain suitable soil biotic habitat
SF_5 = respond to management and resist degradation

The evaluation of each soil quality element will take the form of a functional relationship that describes how the five soil functions listed above impact each of the different soil quality elements.

$$SE_{E1} = f(SF_1,SF_2,SF_3,SF_4,SF_5)$$

$$SE_{E2} = f(SF_1,SF_2,SF_3,SF_4,SF_5)$$

$$SE_{E3} = f(SF_1,SF_2,SF_3,SF_4,SF_5)$$

$$SE_{E4} = f(SF_1,SF_2,SF_3,SF_4,SF_5)$$

$$SE_{E5} = f(SF_1,SF_2,SF_3,SF_4,SF_5)$$

$$SE_{E6} = f(SF_1,SF_2,SF_3,SF_4,SF_5)$$

It is apparent that with this approach, an assessment of soil quality essentially requires the evaluation of six separate functions. The rationale for this approach is necessitated by the fact that soil functions in a duplicitous manner. For example, the attributes at a given site, such as the presence of a clay pan, may serve to retard the leaching of chemicals from the rooting zone, which could be viewed as beneficial from an environmental quality perspective, yet the same clay pan might also restrict the development of crop rooting systems, and thus is detrimental from a productivity standpoint. Thus, different mathematical relationships relating the soil functions to each soil quality element must be developed for each soil quality element.

The next step in the process is to develop mathematical expressions that relate the five soil function components listed above (SF_i) to the set of basic soil attributes or processes shown in Table 1-2. It is recognized that, for each soil quality element, the mathematical expression for a given soil function component SF_i will take a different form. An example of this approach is given where SF_1 is related to soil quality elements SQ_{E1}, SQ_{E2}, and SQ_{E3}. For this example SF_1, the ability to hold, accept, and release water, is represented as a function of infiltration rate and water retention.

$$SF_1 = f(\text{Infiltration rate, Water retention})$$

Theoretical examples of how soil infiltration rate and water retention might be mathematically related to these soil quality elements are presented in Fig. 1-2. It is noted that the mathematical function relating infiltration and water retention to soil quality takes a different form for each of the three soil quality elements. Increased infiltration and water retention result in a higher-quality element rating for crop production (SQ_{E1}), but a lower rating for groundwater quality. Erosivity is independent of water retention in the soil profile and is largely influenced by infiltration. This is the dilemma we are commonly faced with in assessing soil quality; soil properties that enhance one soil quality element may detract from another. Depending on the particular site being assessed, weighting factors based on the intended use of the site will have been predetermined (based on socioeconomic factors) to emphasize the importance of one element over another.

For some soil functions, separate evaluations may be required. For SF_2 (ability to accept, hold, and release nutrients and other chemicals), separate evaluations are required for individual nutrients and chemicals such as N, P, K, heavy metals, and pesticides. It should be noted that these mathematical expressions can be developed to account for regional variations induced by specific cropping systems, geographical location, and climate.

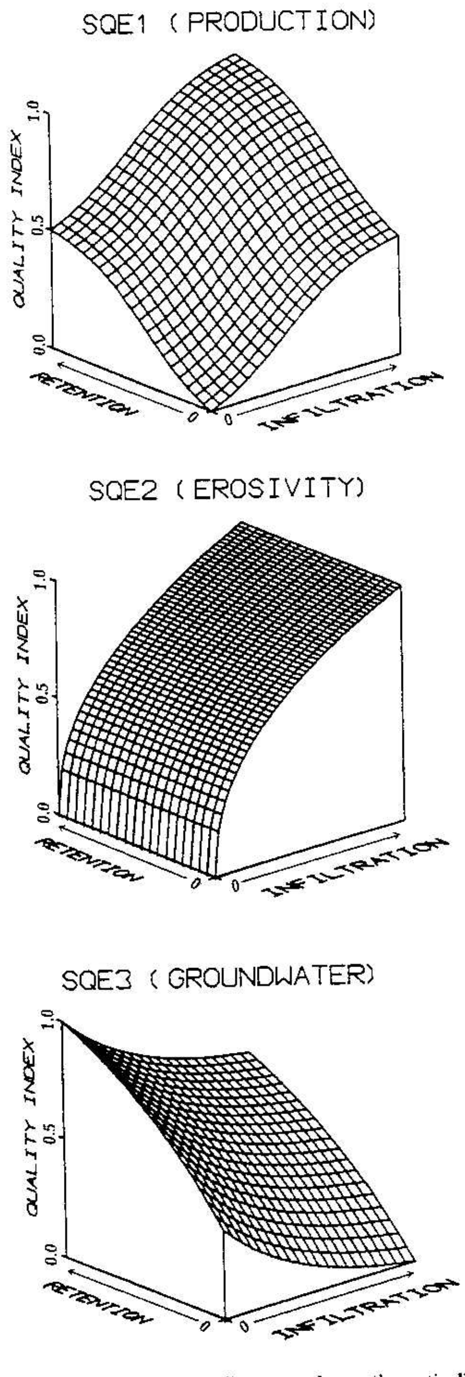

Fig. 1-2. Theoretical examples of how soil attributes can be mathematically related to soil quality elements.

To be of practical use, this approach of defining soil quality based on function, soil function must be related to measurable soil attributes. In the example illustrated in Fig. 1-2, infiltration and water retention could be measured directly or predicted from basic soil attributes (bulk density, organic matter, conductivity) in a manner similar to the pedotransfer functions described by Larson and Pierce (1991; Chapt. 3, this book, 1994). The development of relationships between soil attributes and soil functions may be a monumental task. However, algorithms in existing simulation models (e.g., NLEAP, EPIC, CREAMS, GLEAMS, WEPP) may serve as a useful starting point.

The purpose of this proposed approach to a soil quality index is not to replace previous work in the area of soil quality assessment; rather, it is intended to complement past work by presenting a more clearly defined framework for the development of mathematical relationships, driven by basic soil attributes, to define soil quality. The proposed approach encompasses the flexibility required to be effective over a range of ecological and socioeconomic situations.

CONCLUSION AND NEEDS

There is great need both to determine the status of and to enhance soil resources. Assessment and monitoring of soil quality must also provide opportunity to evaluate and redesign soil and land management systems for sustainability. We need standards of soil quality to determine what is good or bad and to find out if soil management systems are functioning at acceptable levels of performance. We see the following areas as research needs critically important to assessment and enhancement of soil quality. Although we have discussed many of these needs in this chapter, most have been alluded to by authors of other chapters in this soil quality publication.

1. For valid comparison of soil quality across variations in climate, soil, and management, we must establish reference guidelines and thresholds for soil quality indicators that enable interpreting relationships between measured soil attributes and soil function. This will require establishing appropriate scales of time and space for soil quality assessment and standardizing methods and protocols for sampling, processing, and analysis.
2. Develop a practical index for on-site assessment of soil quality by farmers, researchers, extension personnel, and environmental monitorers that can also be used by resource managers and policymakers.
3. Determine the effects of soil quality on plant growth, nutritional composition, and related animal and human health. Provide standards for food quality in terms of specified levels of key nutrients. Identify indicators of soil quality that can be related to food quality and human health.

4. Assess the current status of the biological, physical, and chemical properties of benchmark soils in major management groups throughout the USA. This research would extend information currently being collected by USDA-SCS and SAES soil surveys and genesis and morphology surveys. This assessment should be coordinated with the USEPA sponsored EMAP (Environmental Monitoring and Assessment Program) to which considerable resources have already been committed.
5. Determine the effects of current cropping and management systems and proposed sustainable systems on organic matter levels and other soil properties. Assess the relative effects of increasing or decreasing soil organic matter levels in managed soil ecosystems on atmospheric CO_2 and other enviornmentally important gases and on global climate change predictions.
6. Develop methods and criteria for socioeconomic assessment of soil and land management systems. Estimate economic impacts of improving *soil quality* including increased productivity, increased pollution abatement, decreased sedimentation, increased nutrient use efficiency, and decreased use of energy in crop production. Evaluate how soil quality assessment can be used to estimate economic return from public investment in conservation practices such as the Conservation Reserve Program.
7. Identify biological indicators of soil quality that assess soil biological diversity and food-chain levels in soil as related to soil biological health and nutrient cycling.
8. Develop precision farming techniques for quality enhancement of soils. Establish management practices necessary to attain the biological diversity and food-chain levels for acceptable sustainability.
9. Develop sensors and sensing technology for static and real-time measurement of key variables that define soil quality or are indicative of changes in soil quality. Develop remote sensing capabilities for large-scale assessment of soil quality changes over time.

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